DESY 99-154
hep-ph/9910329
September 1999

Theory of Elastic Vector Meson Production*

Thomas Teubner

Deutsches Elektronen-Synchrotron DESY, Notkestrasse 85, D-22607 Hamburg, Germany

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* Presented at the *Ringberg Workshop: New Trends in HERA Physics 1999*, Ringberg Castle, Tegernsee, Germany, 30. May – 4. June 1999.

Theory of Elastic Vector Meson Production

Thomas Teubner

Deutsches Elektronen-Synchrotron DESY, Notkestrasse 85, D-22607 Hamburg, Germany

Abstract. The elastic production of vector mesons at HERA is discussed from the theoretical point of view. We briefly review different models, their successes and shortcomings. Main emphasis is put on recent issues in perturbative QCD calculations. Models including the vector meson wave function are compared with an approach based on parton-hadron duality. We discuss several refinements of these models in some detail, including the important role of off-diagonal parton distributions.

1 Introduction

Why are we interested in elastic vector meson production? First of all the process $\gamma^* p \to Vp$ provides us with well distinguishable experimental signals in a wide range of the $\gamma^* p$ c.m. energy W, the virtuality of the photon Q^2, and the mass of the vector meson M_V. Quite some data are already available for $V = \rho, \phi$ and J/Ψ, and even for the heavy Υ first measurements were published recently.[1] In the future the range in Q^2 and W and the precision of the data will increase. This enables us to study vector meson production in detail in the very interesting regime where the transition from soft to hard QCD dynamics is expected (and already seen) to take place. In addition, there is hope to make use of the high sensitivity of this process on the gluon distribution $x\, g(x, \overline{Q}^2)$ in the proton to constrain this quantity at small values of x better than through other processes.

In the following we first sketch the basic picture of elastic vector meson production. In Section 2 we briefly discuss different theoretical models which are not based on the two gluon exchange picture which is then introduced in Section 3. There, starting from the basic leading order result known for long time, we develop corrections which improve the leading order formula. In Section 4 recent issues in pQCD calculations as off-diagonal parton distributions, the influence of the vector meson wave function and an alternative approach using parton-hadron duality are discussed. We mainly concentrate on diffractive ρ meson electroproduction, but the presented perturbative model is also successful in the case of J/Ψ and Υ. Section 4 contains our conclusions and outlook.

1.1 The basic picture

In Fig. 1 the basic picture for the process $\gamma^* p \to Vp$ is shown: first the photon with virtuality $Q^2 = -q^2$ fluctuates into a quark-antiquark pair. This $q\bar{q}$

[1] For the discussion of experimental results on the production of light and heavy quarkonia see [1,2,3] and references therein.

fluctuation then interacts elastically with the proton p, where the zig-zag line represents the (for the moment unspecified) elastic interaction with the proton. The $\gamma^* p$ centre-of-mass energy is denoted by W,

$$W^2 = (q + p)^2\,, \tag{1}$$

whereas

$$t = (p - p')^2 \tag{2}$$

is the four-momentum transfer squared. (In the following we will mainly restrict ourselves to the case of small t.) The shaded blob at the right stands for the formation of the vector meson V, which, to leading order, has to form from the $q\bar{q}$ pair with invariant mass squared M_V^2. It is important to note that at high

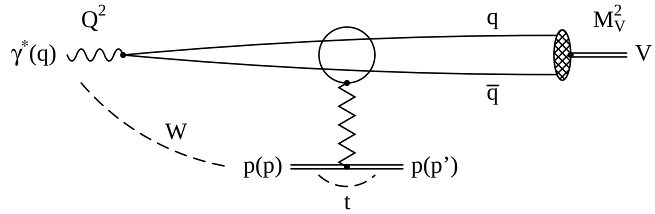

Fig. 1. Diagram for the elastic production of a vector meson V in $\gamma^* p$ collisions

energy W corresponding to small values of x,

$$x = \frac{Q^2 + M_V^2}{Q^2 + W^2}\,, \tag{3}$$

the timescales involved in the problem are very different[2]: the typical lifetime of the $\gamma^* \to q\bar{q}$ fluctuation as well as the time for the formation of the vector meson V is much longer than the duration of the interaction with the proton, i.e. $\tau_{\gamma^* \to q\bar{q}}$, $\tau_{q\bar{q}\to V} \gg \tau_i$. Therefore the basic amplitude factorizes, as sketched already in Fig. 1, into the $q\bar{q}$ fluctuation, the interaction amplitude $A_{q\bar{q}+p}$ and the wave function of the vector meson V,

$$A(\gamma^* p \to V p) \;=\; \psi^{\gamma}_{q\bar{q}} \otimes A_{q\bar{q}+p} \otimes \psi^{V}_{q\bar{q}}\,, \tag{4}$$

and the process becomes calculable within various models.[3] Formally it has been shown that for Q^2 larger than all other mass scales in the process there is factorization into a hard scattering subprocess, non-perturbative (and off-diagonal, as will be discussed later) parton distributions and the meson wave function.[5] This strict proof of factorization holds for longitudinally polarized photons, whereas meson production through transversely polarized photons is shown to be suppressed by a power of Q.

Let us now turn to the discussion of different models for the $\gamma^* p$ interaction.

[2] This definition for x, which is often called ξ or $x_{I\!P}$, is common in diffractive physics and should not be confused with the ordinary Bjorken-x, $x_{\rm Bj} = Q^2/(Q^2 + W^2)$.

[3] For a more detailed discussion of the ordering of the timescales see e.g. [4].

2 Some non-perturbative models

The following short section is far from being a review of this rich field, but is intended to give a hint at some non-perturbative models, which contrast the perturbative description of diffractive scattering, which is the main subject of this article.

• We will not cover approaches based on vector meson dominance (see e.g. [6]).

• For Regge-phenomenology-based models of (one or two) Pomeron exchange we refer the reader to [7].

• *The model of the stochastic QCD vacuum*
Dosch, Gusset, Kulzinger and Pirner [8] have developped a model of the interaction with the proton, which is similar to the semi-classical model of Buchmüller discussed in [9] in the context of inclusive diffractive DIS. This model, originally used for hadron-hadron scattering, leads to linear confinement and predicts a dependence of the high-energy scattering on the hadron size. It gives a unified description of low energy and soft high-energy scattering phenomena. Dosch et al. approximate the slowly varying infrared modes of the gluon field of the proton by a stochastic process. Via a path integral method they average over all possible field configurations. For the splitting of the photon into the $q\bar{q}$ pair and for the description of the vector meson they use light cone wavefunctions. Within their model they are able to calculate the Q^2 dependence of the cross section, as well as the dependence on the momentum transfer t, $\mathrm{d}\sigma/\mathrm{d}t$, and the ratio of the longitudinal to the transverse cross section, L/T, where longitudinal and transverse refer to the polarization of the photon. Their results are in fair agreement with experimental data. There is no prediction for the W dependence of the cross section.

• Rueter has extended the model of Dosch et al. to also describe the W dependence of the cross section.[10] He achieves this by using a phenomenological model based on the exchange of one soft and one hard Pomeron, each being a simple pole in the complex angular momentum plane, similar to the Donnachie-Landshoff model [7]. For the very hard components of the photon fluctuations he treats the interaction perturbatively and achieves a good description of the experimentally observed transition from the soft to the hard regime.

3 The two gluon exchange model

To leading order in QCD the zig-zag line in Fig. 1, which stands for the elastic scattering via the exchange of a colourless object with the quantum numbers of the vacuum, can be described by two gluons. If the scale governing the (transverse) size of the photon fluctuation is large compared to the typical scale of non-perturbative strong interactions, i.e. if

$$Q^2 \gg \Lambda^2_{\mathrm{QCD}} \quad \text{or} \quad M_V^2 \gg \Lambda^2_{\mathrm{QCD}} \,, \tag{5}$$

then the coupling of the two gluons to the $q\bar{q}$ fluctuation can be treated reliably within perturbative QCD (pQCD). Another kinematic regime, where pQCD is applicable, is high-t diffraction. There the hard scale which is needed to ensure the validity of the perturbative treatment is given by the large value of the momentum transfer t, and one expects high-t diffractin to be a good place to search for the perturbative Pomeron.[11]

It has been shown some time ago that due to the factorization property of the process the coupling of the two gluons to the proton can, in the leading logarithmic approximation, be identified with the ordinary (diagonal) gluon distribution in the proton.[12,13,14] We will come back to this point later when discussing the importance of off-diagonal gluon distributions.

3.1 The basic formula

The basic leading order formula for diffractive vector meson production is given by [12,13]

$$\frac{\mathrm{d}\sigma}{\mathrm{d}t}\,(\gamma^* p \to V p)\Big|_{t=0} = \frac{\Gamma_{ee}^V M_V^3\,\pi^3}{48\alpha}\,\frac{\alpha_s(\overline{Q}^2)^2}{\overline{Q}^8}\left[x\,g(x,\overline{Q}^2)\right]^2\left(1+\frac{Q^2}{M_V^2}\right)\,, \tag{6}$$

where α is the electromagnetic coupling and the gluon distribution is sampled at the effective scale

$$\overline{Q}^2 = \left(Q^2 + M_V^2\right)/4\,. \tag{7}$$

In Eq. (6) the non-relativistic approximation for the vector meson wave function is used and the coupling of the vector meson to the photon is encoded in the electronic width Γ_{ee}^V. Note that Eq. (6) is valid for $t = 0$. In the approach discussed in the following there is no prediction for the t dependence of the cross section, which is assumed to be of the exponential form $\exp(-b|t|)$ with an experimentally measured slope-parameter b, which may depend on the vector meson V and on Q^2. On the other hand, Eq. (6) makes predictions for both the Q^2 and the W dependence of the cross section for longitudinally and transversely polarized photons for all sorts of vector mesons, as long as either Q^2 or M_V^2 is large enough to act as the hard scale. It is obvious that the W dependence comes entirely from the gluon distribution $x\,g(x,\overline{Q}^2)$, which enters quadratically in the cross section.

3.2 Improvements beyond the leading order

In the following we will discuss several improvements of the leading order formula.[4]

• Eq. (6) contains only the leading imaginary part of the positive-signature amplitude

$$A \propto i\left(x^{-\lambda} + (-x)^{-\lambda}\right)\,. \tag{8}$$

[4] For more detailed discussions see e.g. [15,16] or the recent review [17].

The real part of the amplitude can be restored using dispersion relations:

$$\mathrm{Re}A = \tan(\pi\lambda/2)\,\mathrm{Im}A\,, \tag{9}$$

where λ is given by the logarithmic derivative

$$\lambda = \frac{\partial \log A}{\partial \log(1/x)}\,. \tag{10}$$

For the case of ρ production, the contributions from the real part are roughly 15%. For J/Ψ production in the HERA regime they amount to approximateley 20% and are even bigger for Υ production [18,19], where larger values of x are probed.

• In Fig. 2 one of four leading order diagrams[5] for the two gluon exchange model is shown with some kinematic variables which will be used below. In the general case the two gluons g_1, g_2 have different x, x' and transverse momenta ℓ_T, ℓ'_T. The leading logarithmic approximation of the ℓ_T^2 loop integral (indicated by the circle in Fig. 2) leads to the identification with the integrated gluon distribution $x\,g(x,\overline{Q}^2)$ at the effective scale $\overline{Q}^2$ defined in Eq. (7). Beyond leading logarithmic accuracy one has to perform the ℓ_T^2 integral over the unintegrated gluon distribution $f(x,\ell_T^2)$. This can lead to numerical results which are, depending on the kinematical regime, twice as big as the result from Eq. (6).[15,4]

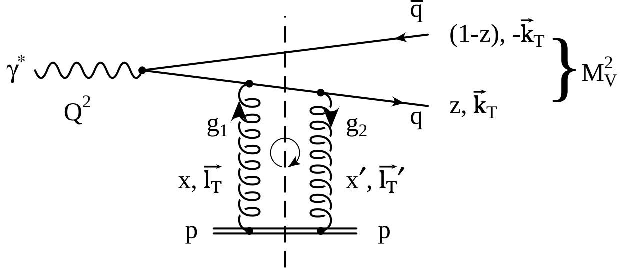

Fig. 2. One of four leading order diagrams for the two gluon exchange model for diffractive vector meson production

Although here we are considering elastic production at small momentum transfer t, the timelike vector meson with mass M_V has to be produced from the spacelike (or real) photon with virtuality Q^2. This means, that even if there is no transverse momentum transfer, $\ell_T = \ell'_T$, there has to be a difference $x - x' = \left(M_V^2 + Q^2\right) / \left(W^2 + Q^2\right)$ in the longitudinal momentum of the two gluons g_1 and g_2. Therefore the identification with the ordinary diagonal gluon

[5] There are three similar diagrams: one where both gluons couple to the antiquark and two where one gluon is attached to the quark, whereas the other couples to the antiquark.

distribution $x\,g(x,\overline{Q}^2)$ is only a good approximation for very small values of x and t, and in the general case the process $\gamma^* p \to V p$ depends on off-diagonal parton distributions.[20] Their importance for diffractive vector meson production will be discussed in the following.

4 Recent issues in pQCD calculations

4.1 Off-diagonal parton distributions

Off-diagonal (also called "skewed" or non-forward) parton distributions[6] are much studied recently.[7] In the case of small t scattering the skewedness comes from the difference between x and x' of the two gluons g_1 and g_2, and the cross section can be shown to be proportional to the square of a skewed gluon distribution,

$$\sigma \propto \left| x' g\left(x, x'; \overline{Q}^2\right)\right|^2 . \tag{11}$$

Here $x = \left(M_{q\bar{q}}^2 + Q^2\right) / \left(W^2 + Q^2\right)$, $x' = \left(M_{q\bar{q}}^2 - M_V^2\right) / \left(W^2 + Q^2\right) \quad \ll \quad x$, and $M_{q\bar{q}}^2$ is the mass squared of the intermediate $q\bar{q}$ pair. (Taking the leading imaginary part of the amplitude corresponds to cutting the amplitude as indicated by the dashed line in Fig. 2 and putting both q and $\bar{q}$ on-shell, which in turn fixes x. x' has to accomodate the difference between $M_{q\bar{q}}$ and M_V and it not fixed due to the integration over all possible quark (and antiquark) momenta. At leading logarithmic order $x' \ll x$ and we can put $x' \simeq 0$.)

For arbitrary kinematics skewed parton distributions are not connected with the diagonal ones and are unknown non-perturbative objects. However, in the case of small x, they are determined completely by the diagonal ones.[21,20] The ratio of skewed to diagonal gluon distribution is given by

$$R_g \;=\; \frac{x' g(x, x')}{x\, g(x)} \;=\; \frac{2^{2\lambda+3}}{\sqrt{\pi}} \frac{\Gamma\left(\lambda + \frac{5}{2}\right)}{\Gamma\left(\lambda + 4\right)} . \tag{12}$$

Here Γ is the usual Gamma-function and the effective power λ can be obtained from the logarithmic derivative of the amplitude A for the $\gamma^* p \to V p$ cross section,

$$\lambda = \frac{\partial \log A}{\partial \log\left(1/x\right)} . \tag{13}$$

As will be shown below, the magnitude of the resulting correction factor for the total cross section, R_g^2, can be sizeable, especially for large Q^2 or M_V^2.

[6] These off-diagonal parton distributions are not parton densities in the ordinary probabilistic sense but matrix elements of parton-fields between different initial and final proton states.

[7] See [20] and references therein.

4.2 The vector meson wave function

Another important issue is the treatment of the vector meson wave function. As sketched in Fig. 1 and Eq. (4) it enters the amplitude via a convolution with the scattered $q\bar{q}$ fluctuation. In Eq. (6) the non-relativistic approximation was adopted. This means, that quark and antiquark equally share the longitudinal momentum of the photon, i.e. $z = 1 - z = 1/2$, and that there is no internal (transverse) momentum k_T in the $q\bar{q}$ bound state. Therefore, in this naive approximation,

$$\psi^V_{q\bar{q}}(z, k_T) \;=\; \delta^{(2)}(k_T)\,\delta\,(z - 1/2)\;, \tag{14}$$

and $M_V = 2m_q$. While this simplification may be suitable for heavy mesons like the Υ, it is clear that the non-relativistic approximation has to break down for light quarks. Various groups have worked on improving this approximation by including the Fermi motion of the quarks in the meson by using a nontrivial wave function.[13,16,15,22] Different models for the meson wave function were used which lead to quite different correction factors: whereas in Gaussian models there is no strong suppression [15], the large k_T tail typical for wave functions from non-relativistic potential models seems to lead to large corrections [16]. On the other hand, considering that within these potential models a big part of the $\mathcal{O}(v^2)$ corrections comes from a regime, where k_T is bigger than the quark mass itself, these large corrections may well be an artefact of the non-relativistic approximation.

Another related problem is the question, which mass for the quarks should be used in the perturbative formulae. Note that Eq. (6) is written in terms of the vector meson mass M_V. However, as discussed in [15], the full expressions used to include higher order (relativistic) corrections contain the quark mass m_q instead of M_V. As the ratio $M_V/(2m_q)$ enters with a high power, this difference is not negligible and should be taken into account in the calculation of the $\mathcal{O}(v^2)$ corrections applied to Eq. (6).

In addition, it is well known that there are other relativistic corrections, which in principle have to be taken into account in a consistent way. As pointed out by Hoodbhoy [23], gauge invariance is only preserved if higher Fock states ($q\bar{q}g$, $q\bar{q}gg, \ldots$) are included in the wave function. In doing so he arrives at the conclusion, that the relativistic corrections to the quark propagators plus the corrections from the higher Fock states amount to only a few percent for J/Ψ production, in agreement with [15].

After all large relativistic corrections can probably be excluded, but, as different approaches lead to quite different results there remains a considerable uncertainty and the issue a hot topic.

4.3 An alternative approach based on parton-hadron duality

In this section we will discuss an alternative approach, which avoids the meson wave function and leads to results which are in surprisingly good agreement with available data. It was proposed in [24] for ρ meson electroproduction, where the hard scale is provided by Q^2, not by M_ρ.[8] Due to the tiny u and d quark masses, in the case of the ρ non-relativistic approximations cannot be justified, and the wave function is not very well known. Now the crucial problem was, that all naive predictions for the ratio of the longitudinal to the transverse cross section, which are based on the perturbative formula (6), lead to

$$\sigma_L/\sigma_T \sim Q^2/M_\rho^2\,. \tag{15}$$

This is much too steep and incompatible with experimental data (see below). The inclusion of effects from a light cone wave function for the ρ does not change the picture considerably.[9] These observations indicate that the main effects are not coming from the ρ wave function and lead to the proposal of a different model in [24]: there the cross section for ρ production is predicted via perturbative $u\bar{u}$ and $d\bar{d}$ quark pair electroproduction together with the principle of parton-hadron duality (PHD) [25]. PHD means that the integral of the parton ($q\bar{q}$) production cross section over a mass interval ΔM is approximately equal to the sum over all (corresponding) possible hadron production cross sections in the same mass interval. In the region $M_{q\bar{q}}^2 \approx M_\rho^2$ the production of more complicated partonic configurations (like $q\bar{q}+g$, $q\bar{q}+2g$, $q\bar{q}+q\bar{q}$, etc.) is heavily suppressed. On the hadronic side the ρ resonance (plus the small admixture of the ω) with its decay into two (three) pions completely saturates the cross section. Therefore we can well approximate the ρ production cross section

$$\gamma^* p \to \rho\, p \to \pi\pi\, p$$

by

$$\sigma\left(\gamma^* p \to \rho\, p\right) \simeq 0.9 \sum_{q=u,d} \int_{M_a^2}^{M_b^2} \frac{\mathrm{d}\sigma\left(\gamma^* p \to (q\bar{q})p\right)}{\mathrm{d}M^2} \tag{16}$$

where M_a and M_b have to be chosen to embrace the ρ resonance appropriately, i.e. $M_b^2 - M_a^2 \sim 1\ \mathrm{GeV}^2$. The factor 0.9 on the right side of Eq. (16) corrects for the contributions from ω production.

The perturbative formulae for the $q\bar{q}$ production cross section are derived from the amplitudes depicted in Fig. 2 and can be written in terms of the conventional spin rotation matrices $d^J_{\lambda\mu}(\theta)$ (see [24] for details):

$$\left.\frac{\mathrm{d}^2\sigma_L}{\mathrm{d}M^2 dt}\right|_{t=0} = \frac{4\pi^2 e_q^2\alpha}{3}\,\frac{Q^2}{(Q^2+M^2)^2}\,\frac{1}{8}\int_{-1}^{1}\mathrm{d}\cos\theta\ \left|d^1_{10}(\theta)\right|^2 \left|I_L\right|^2\,, \tag{17}$$

$$\left.\frac{\mathrm{d}^2\sigma_T}{\mathrm{d}M^2 dt}\right|_{t=0} = \frac{4\pi^2 e_q^2\alpha}{3}\,\frac{M^2}{(Q^2+M^2)^2}\,\frac{1}{4}\int_{-1}^{1}\mathrm{d}\cos\theta\ \left(\left|d^1_{11}(\theta)\right|^2 + \left|d^1_{1-1}(\theta)\right|^2\right) \left|I_T\right|^2$$

[8] Experimentally both the t dependence $\mathrm{d}\sigma/\mathrm{d}t \sim \exp(-bt)$ with $b \simeq 5-6\ \mathrm{GeV}^{-2}$ for $Q^2 > 10\ \mathrm{GeV}^2$ and the W behaviour of the cross section $\sigma \propto W^{0.8}$ indicate that ρ meson electroproduction is not a soft, but mainly a hard process.

[9] One might argue that σ_T receives large contributions from the small k_T region, which is non-perturbative. But those contributions would cause the transverse cross section to fall off even faster with increasing Q^2 and therefore worsen the problem [24].

where e_q is the electric charge of the quark q, α the electromagnetic coupling and θ the polar angle of the quark q in the $q\bar{q}$ rest frame with respect to the proton direction ($k_T = M/2\sin\theta$). $I_{L,T}$ are integrals over the gluon ℓ_T^2 and given by

$$I_L(K^2) = K^2 \int \frac{\mathrm{d}\ell_T^2}{\ell_T^4}\, \alpha_s(\ell_T^2)\, f(x,\ell_T^2) \left(\frac{1}{K^2} - \frac{1}{K_\ell^2}\right), \tag{18}$$

$$I_T(K^2) = \frac{K^2}{2} \int \frac{\mathrm{d}\ell_T^2}{\ell_T^4}\, \alpha_s(\ell_T^2)\, f(x,\ell_T^2) \left(\frac{1}{K^2} - \frac{1}{2k_T^2} + \frac{K^2 - 2k_T^2 + \ell_T^2}{2k_T^2\, K_\ell^2}\right),$$

with f being the unintegrated gluon distribution and

$$K_\ell^2 \equiv \sqrt{(K^2 + \ell_T^2)^2 - 4k_T^2\ell_T^2}\,, \qquad K^2 \equiv k_T^2(Q^2 + M^2)/M^2\,.$$

In Eqs. (17) the different rotation matrices appropriately reflect the different spin states of the $q\bar{q}$ produced from longitudinal and transverse photons, and the integrals $I_{L,T}$ contain the scattering off the proton via the two gluon exchange.[10] In order to pick up only those $u\bar{u}$, $d\bar{d}$ configurations which correspond to the quantum numbers of the ρ, one has to project out the $J^{PC} = 1^{--}$ states. This can be easily done on amplitude level with the same rotation matrices $d^J_{\lambda\mu}(\theta)$, see [24]. (Even higher spin states like the $\rho(3^-)$ can be projected out using the corresponding d function [26].) It is important to note that through the projection on amplitude level the longitudinal and transverse cross sections $\sigma_{L,T}$ are less infrared sensitive than Eqs. (17), and therefore σ_T becomes calculable without a large uncertainty from the treatment of the (non-perturbative) infrared region.

For the complete numerical predictions one also has to include the contributions from the real part of the amplitudes and the skewed gluon distribution as discussed above. Both effects are taken into account on amplitude level. Eqs. (17) give the cross section differential in t for $t = 0$. To arrive at the t integrated total cross section one assumes the exponential form $\exp(-b|t|)$. The slope b can be taken from experiment or theoretical models and depends in general on M^2, W and Q^2. For more details we refer the reader to [27].

To go beyond the leading order prediction in a completely consistent way would require in addition the full set of next-to-leading order gluonic corrections to the $(q\bar{q})$-$2g$ vertex. These corrections are not known yet[11], but can be estimated by a $\mathcal{K}$ factor [4,24]. Similar to the Drell-Yan process, there are π^2 enhanced terms, which come from the $i\pi$ terms in the double logarithmic Sudakov form factor. Resummation of those leading corrections results in the $\mathcal{K}$ factor $\mathcal{K} = \exp(\pi C_F \alpha_s)$ which leads to a considerable enhancement of the cross section.

[10] Here we assume s channel helicity conservation (SCHC), i.e. the produced ρ has the helicity of the virtual photon. However, there are small violations of SCHC (e.g. $\gamma_T^* \to \rho_L$) which can be successfully described in a framework similar to the one discussed here. For a discussion of recent measurements of the 15 spin density matrix elements of ρ production compared to different theoretical predictions see [1].

[11] A first step towards the calculation of the full NLO corrections is provided by [28].

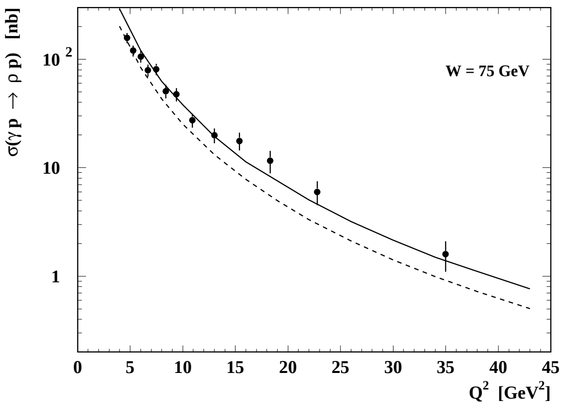

Fig. 3. $\sigma\,(\gamma^* p \to \rho\, p)$ predicted within the PHD model as described in the text compared to recent H1 data [29]. *Continuous line*: using the skewed gluon distribution, *dashed line*: without skewing

In Fig. 3 the complete numerical prediction for $\gamma^* p \to \rho\, p$ using the PHD model[12] is shown as a function of Q^2 together with recent H1 data.[29] The continuous line includes all the effects discussed above, whereas the dashed line does not include the skewed gluon. The importance of the off-diagonal gluon for the Q^2 behaviour of the cross section is obvious and the effect seems to be required to describe the data. Of course the model prediction is not free from uncertainties like the choice of the mass interval $M_b^2 - M_a^2$ in Eqs. (16) or the scale of α_s in the $\mathcal{K}$ factor. These (and other) uncertainties are discussed in detail in [27], but they affect mainly the normalization of the cross section and do not spoil the good agreement with the experimental data. In Fig. 4 the prediction of the PHD model for the ratio L/T is shown as a continuous line. It agrees fairly well with the data points, which show a very modest rise with Q^2 in contrast to the naive prediction Eq. (15) (dashed line). Thus, in the PHD picture, it is *not* the ρ wave function, but the dynamics of the $q\bar{q}$ pair creation from longitudinal and transverse photons together with the off-diagonal two gluon interaction and the projection onto the 1^- state, that determines the Q^2 dependence and the ratio L/T.

It is important to note that the PHD model also works in the case of massive quarks and heavy mesons. Starting from formulae for diffractive heavy quark production [4] and modifying the projection formalism appropriately, elastic Υ photoproduction was recently predicted using PHD in agreement with first measurements.[18] The same formalism can also be applied to diffractive J/Ψ production.[27] Again, as shown in Fig. 5, there is a surprisingly good agreement between the predicted cross section as a function of Q^2 and the experimental data [33].

[12] For the numerical analysis the MRST99 gluon [30] was used and the scale of α_s in the $\mathcal{K}$ factor was chosen as $2K^2$. For more details see [27].

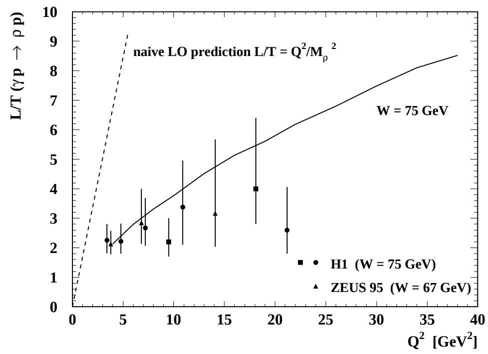

Fig. 4. L/T predicted within the PHD model (*continuous line*) as described in the text compared to experimental data [29,31,32] and the naive prediction (*dashed line*) from Eq. (15)

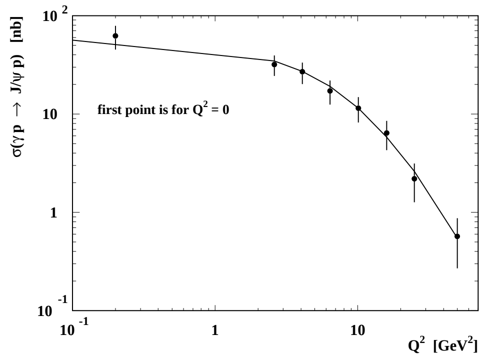

Fig. 5. Cross section for diffractive J/Ψ production as predicted in the PHD model [27] compared to recent H1 data [33]

5 Summary

Elastic vector meson production is a rich field, both from experimental and theoretical point of view. Different theoretical models describe the data, and more precise data in an increased kinematical range will be needed to clarify the situation. We have briefly discussed some non-perturbative models, but mainly concentrated on perturbative approaches. We have shown that with recent improvements pQCD-based approaches work very well and are in agreement with data. The fairly large impact of skewed parton distributions on the predictions within these models is supported by the data. There is good hope that in future we will be able to discriminate between the different models and to understand elastic vector meson production in more detail. By combining different observables from different processes elastic vector meson production with its high sensitivity to the gluon at small x will finally help to constrain the gluon much better. For this much effort will be needed also from the theoretical side in order to increase the precision of the calculations.

Acknowledgements

I would like to thank G. Grindhammer, B. Kniehl and G. Kramer for the good organization of this stimulating and enjoyable workshop. I also thank Genya Levin, Alan Martin and Misha Ryskin for pleasant collaborations.

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